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PARAMETRIC STUDY OF TWISTED TAPE INSERT ON THE HEAT TRANSFER CHARACTERISTICS IN A SQUARE TUBE UNDER TURBULENT CONDITIONS

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ABSTRACT

In the present study, the effect of inserting a twisted tape as a passive device for heat augmentation inside a square tube has been numerically studied under turbulent conditions. A twisted tape with constant pitch has been placed inside a square tube with negligible thickness and numerical simulation was done with Reynolds number (Re) of the fluid varying from 2,500 to 10,000. Heat transfer characteristics like Nusselt number and friction factor have been determined. Initially, the numerical results are validated by comparing with the empirical correlations for the bare tube under constant wall temperature boundary conditions. To study the parametric variation, simulation was conducted for different tape width ratios 0.4, 0.6 and 0.8. Thermo-Hydraulic Performance Index (THPI) was measured and was found to be higher for low Re and found to be reduced as Re increases. Similarly, as the width ratio increases, THPI reduces and optimum value obtained for a width ratio of 0.4. It was concluded that using a passive device like a twisted tape inside a square tube performs better than bare tube and also tape width has a significant influence on the thermohydraulic characteristics in a square heat exchanger.

KEYWORDS: Twisted Tape, Nusselt Number, Friction Factor & Thermo-Hydraulic Performance Index

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Original Article

1. INTRODUCTION

Heat exchangers are widely used in various industries like power plants, refineries, chemical, and petrochemical industries to exchange the heat energy between two fluids. Different configurations of heat exchangers are used in industries, which include double pipe, shell and tube and plate type, etc. To increase the heat transfer rate, without increasing the area of the existing heat exchanger, various types of heat augmentation techniques are used. They include reciprocating plungers or cams that pulse, causing flow modification. The passive method includes surface or geometrical modifications of the base surface, which helps in increasing the heat transfer. Different types of inserts like twisted tapes, wire coil, helical tape, etc., will be inserted into the flow field to induce vortex flow that encourages heat transfer [1,2]. When such inserts are introduced, they completely disturb the flow field inducing spiral, helical motion of the fluid there by inducing more turbulence. The compound method is one wherein both the techniques are used simultaneously, but in most practices, passive techniques are used, as it is very simple to fabricate and use, moreover it does not require any external power for its operation. This promotes the working efficiency [3] [4].

Twisted tapes are the metallic strips twisted to attain desired dimensions. They are inserted in the path of the flow. They are cheap and simple heat augmentation techniques that can be used in augmenting the heat transfer rate in a double pipe heat exchanger. Insertion of this type of insert in the flow field creates a swirl motion for the

fluid. When the fluid moves in the axial direction, it also swirls in the perpendicular direction to its motion. This promotes vigorous mixing of the different fluid layers. This phenomenon helps to reduce the thermal boundary layer near the tube wall and is responsible for increasing the convective heat transfer rate [5]. The physical parameters like pitch of the tape and width of the twisted tape greatly govern the transfer of heat. Several researchers have conducted experimental and numerical studies using twisted tape inserts in circular tubes. Savekar *et al*. [6] investigated the effect of mass flow rate and twist ratio on the heat transfer characteristics inside a circular tube with a twisted tape. Results indicated that as the twist ratio is decreased and Reynolds number is increased, heat transfer rate increased. Gulia *et al.* [7] discussed both the experimental and numerical work conducted in a circular tube with a passive device for the improvement in thermal characteristics. It was observed that on insertion of full-length twisted tape, heat transfer rate as well as friction factor increased. Aggarwal *et al.* [8] experimentally studied the influence of twisted tape on the performance of twisted tape inside a circular pipe. They found the average Nu increased by 2.28–5.35 times, where the friction factor increased by 3.31–9.71 times that of the plain tube.

Square duct has higher surface-to-volume ratio than the circular tube. Hence, a square duct having equal hydraulic diameter of a circular tube reveals higher heat transfer surface area. This helps in increasing the convective heat transfer rate from the tube. Hence, heat exchanges with either rectangular or square cross sections can be considered as an alternative to circular cross-sectioned heat exchangers. Some researchers have investigated the use of different types of inserts in rectangular and square tube for enhancing the heat transfer rate under both laminar and turbulent conditions. Pramanik and Saha [9] studied the use of tapes with internal transverse ribs in rectangular and square tubes. They found that use of ribs with full-length increases the thermohydraulic performance as compared with the performance by using only twisted tape. Ray and Date [10] numerically studied heat transfer characteristics using a square tube heat exchanger with twisted tape as the insert. They found higher thermohydraulic efficiency for a square tape with a tape than a plain tube. Further heat transfer rate was higher (approximately 25%) for a square tube than the circular tube. Saha and Malik [11] experimentally examined the heat transfer characteristics and pressure drop features for a square tube with a twisted tape insert. They considered three types of arrangements, full length, short length and regularly spaced and observed better performance.

Various researchers have carried out both experimental and numerical analysis on the use of various types of inserts in heat exchangers. But it is seen that use of twisted tape type of insert in a square cross-sectioned heat exchanger has not been undertaken by many researchers. Further influence of the tape parameters, especially tape width on the performance characteristics in a square heat exchanger has not been studied by any researcher. Hence, in the current study, performance of the square heat exchanger with a twisted tape is numerically studied and the investigation has been done to examine the flow physics and its influence on the heat transfer characteristics. Further, the simulation has been continued by changing the tape width ratios and their performance were compared with base model, and the results have been presented.

2. THEORETICAL BACKGROUND

Considering a square duct with negligible thickness and selecting water as the fluid flowing inside the duct, general heat transfer equations have been used to find average Nusselt number. Knowing the values of inlet and outlet temperatures, heat transfer rate and heat transfer coefficient can be calculated as displayed in equation 1. Further, Nusselt number can be calculated by using equation 3. For a given hydraulic diameter and length of the tube knowing the values of pressure drop,

friction factor can be calculated by using Equation 5. Equation 6 is used to calculate the Thermo Hydraulic Performance Index.

$$h = \frac{Q}{4DL(T_2 - T_1)}, \tag{1}$$

where Q is the heat transfer rate in Watts, D is the hydraulic diameter, L is the length of the tube.

$$Q = \dot{m}c_p\Delta T \tag{2}$$

$$Nu = \frac{hD}{\mathrm{k}}, \tag{3}$$

where Nu is the Nusselt number, k is the thermal conductivity of the fluid.

$$v = \frac{Re\mu}{\rho \mathrm{D}} \tag{4}$$

Re is the Reynolds number, v is the kinematic viscosity, μ is the dynamic viscosity

$$f = \frac{2\Delta PD}{\rho \mathrm{L} v^2} \tag{5}$$

$$THPI = \frac{\left(\frac{Nu_{tape}}{Nu_{bare}}\right)}{\left(\frac{FrictionFactor_{tape}}{FrictionFactor_{bare}}\right)^{\frac{1}{3}}} \tag{6}$$

3. NUMERICAL MODEL

Initially, the geometry of the twisted tape inserted inside a square heat exchanger is designed as revealed in figures 1 and 2. Specifications of the square heat exchanger dimensions, twisted tape parameters like tape width, twist ratio, etc., mentioned in table 1. Initially, a square pipe is developed, wherein a twisted tape insert is inserted at the center of the heat exchanger. Two separate volumes are created by the Boolean operation. Tetrahedral meshing is used to mesh both the geometries.

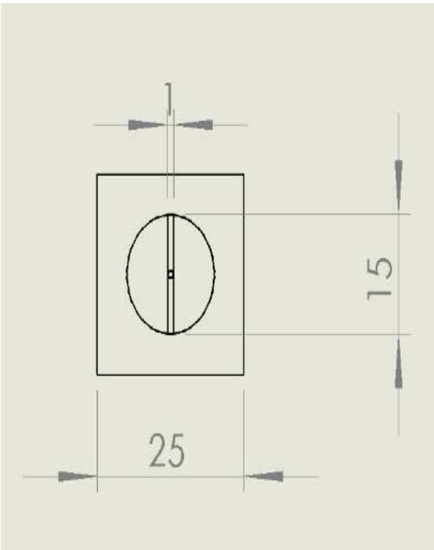

Figure 1: Front view of the Model with Twisted Tape.

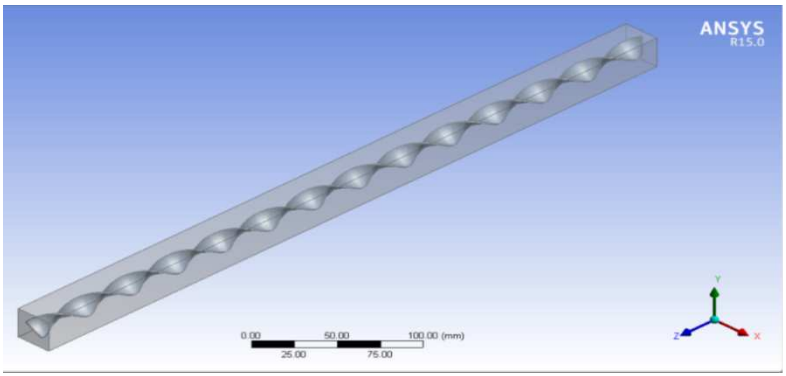

Figure 2: View of Square Pipe Heat Exchanger with Twisted Tape

Table 1: Specifications of the Heat Exchanger and Flow Condition

Specifications	Conditions
Square Heat Exchanger	25 mm × 25 mm
Length	500 mm
Width ratio of Tape	0.4, 0.6 and 0.8
Thickness	1 mm
Tape pitch	50 mm
Material of Tape	Copper
Material of Heat Exchanger	Copper
Working Fluid	Water
Reynolds Number of Water	2500, 5000, 7500, 10000

4. NUMERICAL SOLUTION

Once the geometry is created, it is meshed using tetrahedral elements. After meshing, relevant boundary conditions have been applied. Mass flow rate and water inlet temperature are specified at the inlet, whereas pressure outlet is applied on the outlet. Constant temperature boundary condition is enforced on the outer surface. Appropriate turbulent scheme is selected. Similarly, convergence criteria is selected for the velocity as well as energy. Velocity in all the directions is put at a limit of 0.001, and for energy the corresponding limit applied is 10^{-6}. Initially, simulation is carried out for the plane model without the tape. Grid independence test is carried out to select the optimum number of elements for the study. Obtained results for Nu factor are compared with the available literature and are revealed in figure 1. It is seen that the average error between them is within 3%, which is within the acceptable limits. Hence, the model can be used for further study on the parametric variations of the heat exchanger.

$$Nu = 0.023Re^{0.8}Pr^{0.4} \tag{7}$$

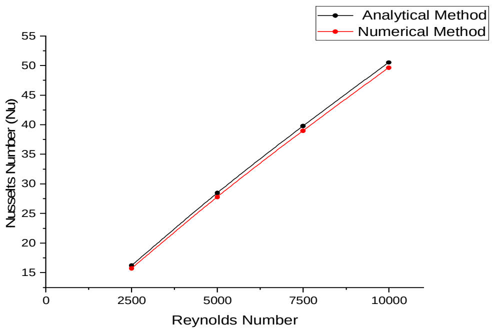

Figure 3. Nu vs Re for Analytical and Numerical Method for the Bare Tube.

5. RESULTS AND DISCUSSIONS

For studying the parametric variations, initially a twisted tape with the dimensions as mentioned in table 1 is modeled and simulated. Further twisted tape with varying width ratios is modeled inside the square pipe, and the study is carried out by changing the Reynolds number. The ratio of the tape width-to-the side of the square heat exchanger is termed as width ratio (WR), and in the present study, simulation is conducted for WR of 0.4,0.6 and 0.8. Simulation is carried out by keeping same boundary conditions as that of bare pipe and the temperature at outlet is noted for all the cases. The Nusselt number, friction factor and THPI are calculated for the above combinations.

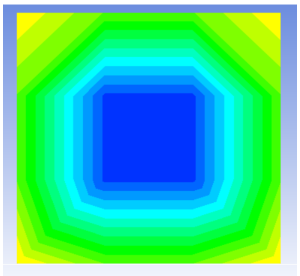

Figure 4(a): Temp. Contour for the Bare.

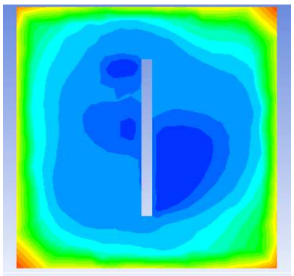

Figure 4(b): Temp. Contour for the Pipe with the Tape.

In order to understand the influence of the tape on the temperature distribution, temperature contour plots have been taken for the heat exchanger with and without the twisted tape, and are revealed in figures 4(a) and 4 (b). For the heat exchanger without the tape, applied high temperature has not been much varied, as can be seen clearly from figure 4(a), whereas in figure 4(b), it is seen that uniform mixing takes place by which the energy transfer from the boundary to the inner surface of the heat exchanger is increased. This is mainly due to the helical motion of the water along the twisted tape geometry, which gives rise to a complete mixing of water during its motion, thereby decreasing the thermal boundary layer near the wall, and hence this contributes to the increase in outlet temperature of water.

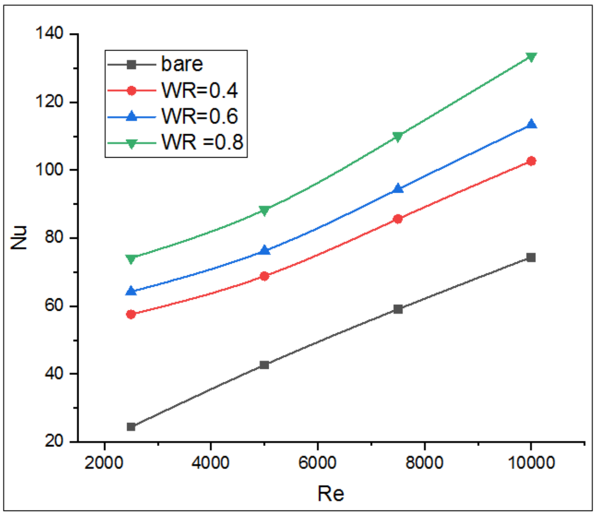

Figure 5: Nusselt Number with Reynolds Number for Varying width Ratios.

Nu is the ratio of convective-to-conductive heat transfer rate across the boundary. It is an indication of how efficiently convective heat transfer occurs from the boundary. For the different tested conditions of the heat exchanger, Nu has been plotted against Re and are displayed in figure 5. The results are also compared with the bare tube. Initially, it is seen that for all cases, Nu increases with the Re and for all WR, it is higher than bare pipe justifying the advantage of

twisted tape inside the square cross-sectioned heat exchanger. Due to the spiral motion of the fluid, thorough mixing takes place, which increases the convective heat transfer. Increase in convective heat transfer increases the Nu. It has been observed that when the width ratio is increased, the Nusselt number is also increased. This is attributed to the amplified amount of swirl generated due to increased twisting area for higher width tapes. Higher swirl that has been generated effectively mixes the fluid, thus further reducing the thermal boundary layer and increasing the heat transfer rate. Highest Nu is obtained for a width ratio of 0.8, which is 17.5% and 30.3% higher than WR of 0.4 and 0.6 at a Re of 10,000.

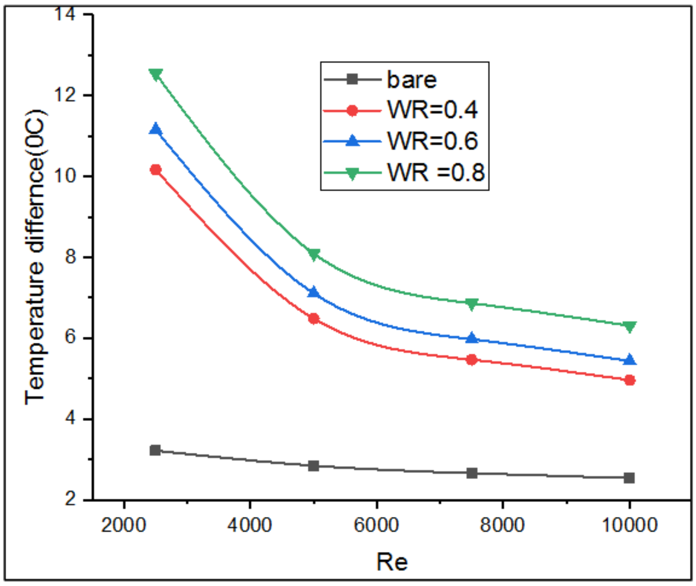

Figure 6: ΔT for Water with Reynolds Number for Varying Width Ratios.

The difference in cold water inlet and outlet temperature (ΔT) is plotted against the Re for the various simulated conditions, as displayed in Figure 6. Outlet temperature decreases, as the Re is increased. Outlet temperature values for twisted tape conditions are found to be higher than the bare square tube. When a passive augmentation device like a twisted tape is inserted, flow field will be disturbed. The flow follows the path of the tape and hence a helical path will be traced by the fluid, by which vigorous mixing takes place in the normal direction, along with its motion in axial direction. Due to this, effective thermal boundary layer near the wall will be reduced and heat transfer characteristics will be improved. Hence, the water outlet temperature will be increased. When the width ratio increases, this effect further increases, increasing the fluid mixing and hence the outlet temperature. For a Re of 10,000 for a tape with WR = 0.8, rise in outlet temperature is around 1.52 times higher than the bare tube.

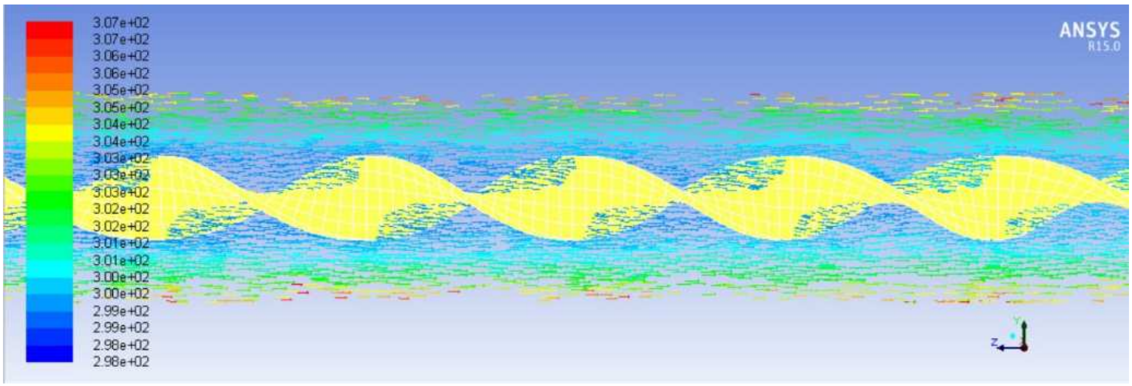

Figure 7: Velocity Vector Plots Colored with Temperature for Tape with WR 0.4

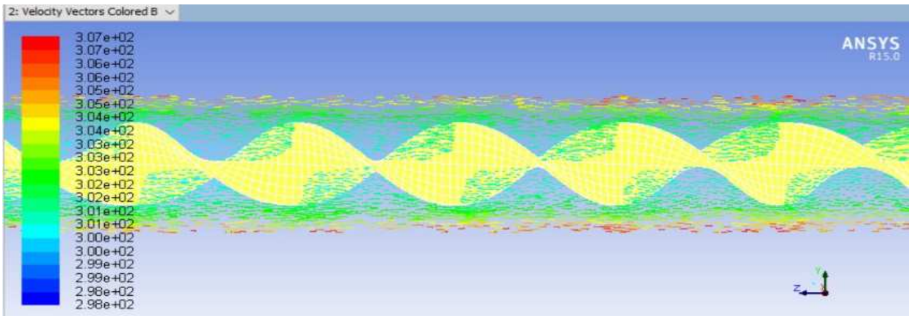

Figure 8: Velocity Vector Plots colored with Temperature for Tape with WR 0.6.

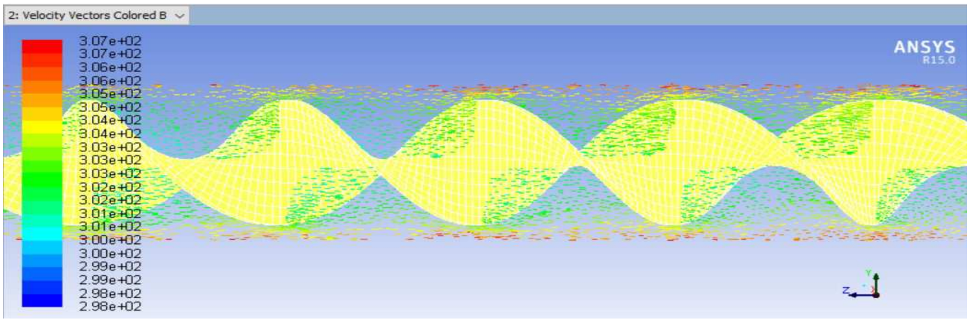

Figure 9: Velocity Vector Plots Colored with Temperature for Tape with WR 0.8.

Figures 7, 8 and 9 represent the velocity vector plots colored with temperature for the tapes with different WRs. It is seen that as the width ratio of the tape increases, the velocity of the fluid will be higher, as the effect of swirl amount increases. This enhances the mixing of the fluid and hence effective heat transfer rate occurs between the fluid and the outer heated surface. As a result, outlet fluid temperature will be higher. As seen from the figures that tape with WR = 0.8, outlet water temperature is higher than the tape with other WRs.

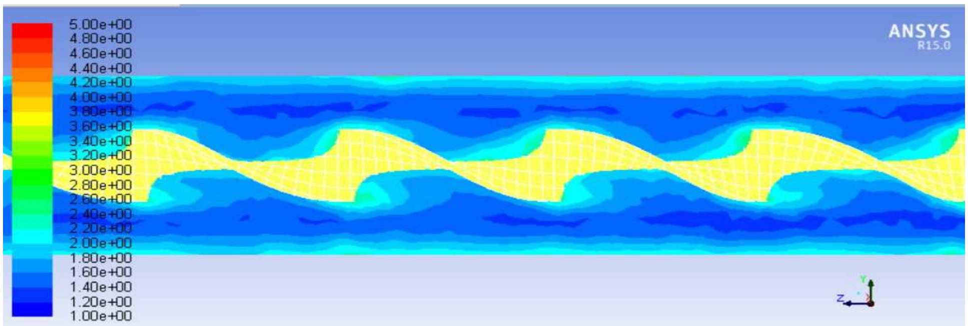

Figure 10: Turbulent Intensity Ratio for Tape with WR is 0.4.

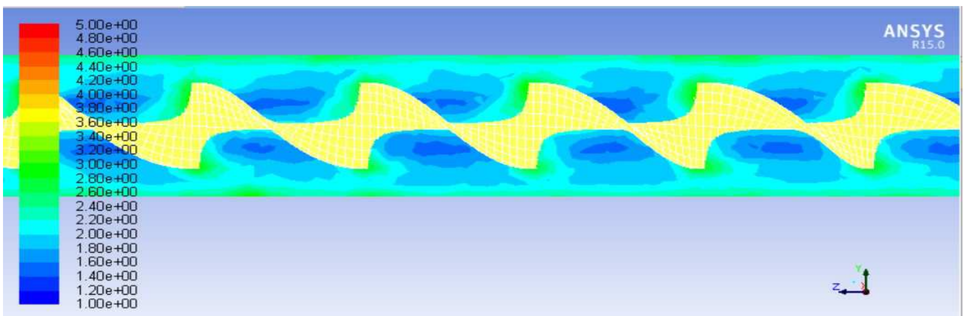

Figure 11: Turbulent Intensity Ratio for Tape with WR 0.6.

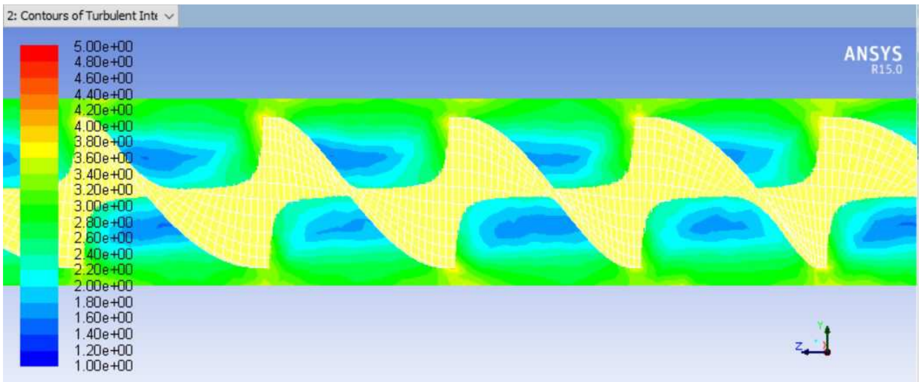

Figure 12: Turbulent Intensity Ratio for Tape with WR 0.8.

Figures 10, 11 and 12 represent the turbulent intensity values for the tape with three different WRs 0.4, 0.6 and 0.8, respectively. As the WR increases, turbulent intensity increases. Higher width tape induces more turbulence because of the intense mixing of different layers of the fluid. When the WR is small, the velocity of the fluid will be lower and hence turbulence will be less. As the WR increases, this effect increases, increasing the fluid velocity as well as the fluid turbulence, as displayed in figure 11.

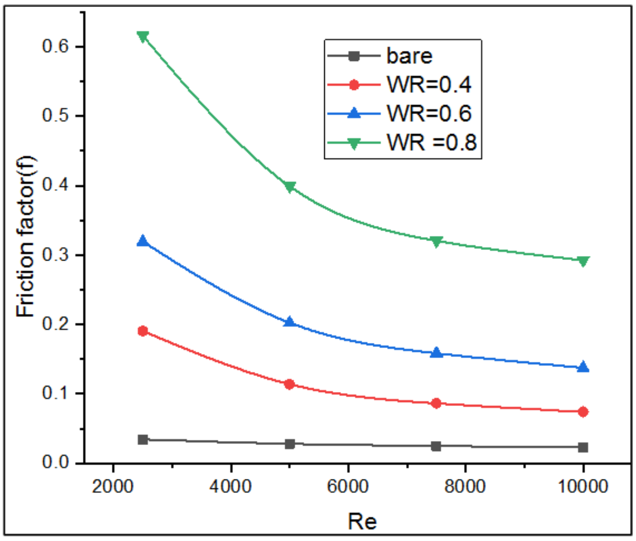

Figure 13: Friction Factor against Reynolds Number with Width Ratios.

Friction losses will occur due to the friction head loss due to friction between fluid and the pipe wall, and also internal friction within the fluid. Friction factor is defined as the ratio between local shear stress and the local kinetic energy density. It is calculated by measuring the pressure difference between the inlet and outlet section of the pipe. For the various tested cases, friction factor f is displayed in figure 13. It is seen from the figure that for the bare tube, it is minimum compared to the cases with twisted tape of any WR. As WR increases, f also increases. This is mainly due to the blockage that is caused by the insertion of the twisted tape along the direction of the fluid flow, and this increases as the WR of the tape is increased. Hence, higher f will be observed. It is seen that for all tested cases, as Re increases, f values decreases due to the increase in velocity for higher Re values. It is found that for a square tube with the twisted tape, maximum friction factor was observed with WR 0.8.

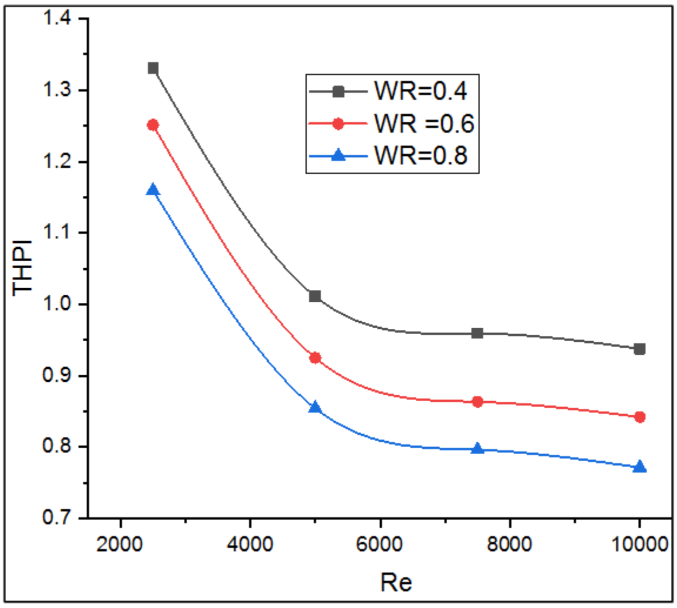

Figure 14: THPI with Reynolds Number for varying width Ratios.

Any fluid flow performance is judged by the comparative analysis of Nu and pressure drop for the various cases and hence a useful factor called Thermo-Hydraulic Performance Index (THPI) is defined. It is seen that as WR increases, Nu increases, simultaneously pressure drop also increases. This means that higher pumping power is required to move the fluid when higher width tapes are inserted. Hence, THPI is defined as

$$\frac{\left(\frac{Nu_{tape}}{Nu_{bare}}\right)}{\left(\frac{FrictionFactor_{tape}}{FrictionFactor_{bare}}\right)^{\frac{1}{3}}}$$

It gives a measure of the performance of the heat exchanger with the heat augmenting device. For the measured cases, THPI is plotted against Re and is displayed in figure 14. It is well understood that as Re increases, THPI drastically reduces, thus justifying the use of twisted tapes in laminar flow conditions. Further, on comparing THPI for different width ratios, it is seen to be maximum for WR 0.4 and minimum for WR 0.8 for any Reynolds number. At Re of 2500, highest values obtained are 1.33 and 0.93, whereas lowest values are 1.15 and 0.77 for WR of 0.4 and 0.8, respectively revealing the reduced performance with the higher Reynolds number. On increasing the WR, increase in the pressure drop will be higher comparatively to the increase in Nu. Hence, their ratio decreases, thus reducing the values of THPI. This indicates that twisted tapes will achieve better with low Re and smaller WRs. As the Re and WR have been increased, their performance deteriorates. However, if the heat transfer characteristics in a square pipe heat exchanger have to be improved, the use of a twisted tape insert with the optimum width ratio is recommended, which would help to improve the efficiency of the heat exchanger.

6. CONCLUSIONS

In the present work, analysis of the square heat exchanger with twisted tape as an insert has been numerically studied for the heat transfer augmentation. Following conclusions can be drawn from the study.

- Insertion of the tape inside the square heat exchanger causes increase in Nu as well as outlet temperature. As the WR is increased, Nu increases and for the width ratio of 0.8, it is increased by 80.4%, as compared to the bare

tube for a Reynolds number of 10,000.

- THPI is higher for smaller width tapes. As the tape width increases, Nu decreases. Highest THPI is observed with the tape of width ratio of 0.4 at Re of 2,500.

From the above study, it can be seen that twisted tape is considered to be a promising passive heat enhancement technique in a square heat exchanger, which can result in reduced energy consumption for any heating and cooling applications.

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